EVALUATION OF SURVEY SYSTEMS

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Introduction

The evaluation of the performance of a given survey system depends primarily on only two parameters: the threshold brightness for detection (limiting magnitude), and the rate of sky coverage. Of much lesser importance are such factors as the geographic location of the observing site(s), the ability to detect rapidly moving objects compared to the sensitivity to stationary targets, and the detailed strategy used to follow up detections to obtain preliminary orbits. For the proposed NEO survey, we will show that the best strategy for maximizing the rate of discovery of NEOs is to cover the entire observable sky each month. An optimum search system should be designed to be capable of fast enough operation to achieve all-sky coverage, sacrificing limiting magnitude as necessary to achieve this goal. Thus we can, within the uncertainties of the models employed, reduce the problem to a single parameter: the limiting magnitude that a given system can deliver in the mode of covering the whole sky each month. The practical achievement of this mode has become possible with the present state of development of CCDs.

In this chapter, we will present the results of a survey simulation to show the level of completeness that can be expected from putative survey systems as a function of time (length of survey), area of sky covered per month (from which we derive the above conclusion for all-sky coverage), and size of NEO. We can then simply relate these results to specific systems through estimates of the limiting magnitude achievable with a given system. In Appendix III we give a more detailed report of the evaluation methods and results for specific systems. In this chapter, we summarize the search strategies and expected capabilities in more general terms.

Survey Systems

For the purpose of a quantitative discussion, we shall evaluate survey completeness for three rather specific systems. However it should be noted that results can easily be scaled to other systems that might be contemplated. The three systems are representative in general terms of systems of 0.5-m, 1-m, and 2-m aperture. Following is a brief description of each system.

1. The Lowell Observatory Near-Earth Object Survey (LONEOS) telescope is a modified Schmidt telescope of 0.58 m aperture, 1.11 m focal length (f/1.91), which is under construction at Lowell Observatory. "First light" is expected during this year. Initially, it will be equipped with a two CCD chips with 2048 x 2048 pixels, 15 microns square, or a field format of 3 cm by 6 cm. Eventually, it is planned to use two butted 2048 x 4096 chips with 15 micron pixels, for a 6 cm square format, which yields an angular field of view 3°.17 on a side, or an area of 10.1 square degrees. It is planned to use front-illuminated, unthinned CCDs with a quantum efficiency of ~25%. We estimate that this system can reach a limiting visual magnitude of 19.4 with 68 second exposures. In our evaluations, we consider the "full-up" system with $(4096)^2$ pixels.

2. The USAF Space Command currently operates a network of 1-m, f/2 wide-field telescopes, the Groundbased Electro-Optical Deep Space Surveillance (GEODSS) system, for tracking Earth satellites. The GEODSS Upgrade Prototype System (GUPS), currently under development, will employ large format CCD detectors, which with only minor modifications and changes to the computer software, might be effectively employed for NEO surveys. The CCD detector under development at Lincoln Laboratory is a single chip of 1960 x 2560 pixels, 24 microns square, or a total format of 4.7 cm by 6.1 cm. In the GEODSS telescope, this yields an angular field of 1°.23 by 1°.61, or 1.98 square degrees. The chip is thinned, back-illuminated, with a quantum efficiency exceeding 75%. We estimate that this system can reach a limiting magnitude of 20.2 with 20 second exposures.

3. The Spacewatch (SW) Telescope on Kitt Peak, Arizona. The present (operating) system is a 0.9 m telescope of 4.6 m focal length (f/5) with a single CCD detector with 2048 x 2048 pixels of 24 microns, or a total format 4.9 cm on a side. The detector is thinned, back-illuminated, with a quantum efficiency of ~75%. SW has a demonstrated limiting visual magnitude of ~21.2 with a 147 second exposure covering a 0.57 square degree field. Since it is the only currently operating system, we have estimated the limiting magnitudes expected for the other systems by scaling from the demonstrated performance of SW.

4. A second telescope (SW-II) of 1.8m aperture and 4.9m focal length (f/2.7) is under construction. Initially, it will be equipped with a similar CCD detector, which will yield a field of view of 0°.57 on a side. In a scanning mode with a 30 second integration time, this system should reach a limiting visual magnitude of 21.5. With this detector and exposure arrangement, SW-II cannot achieve all-sky coverage each month (to be discussed later). It could do so with a mosaic of 4 butted CCD chips, giving a field of view of 1°.14 on a side, and rapid read-out electronics so that it could take individual exposures as short as 10 seconds. The telescope is mechanically and optically capable of accommodating this array and exposure rate. With 10 second exposures, the limiting visual magnitude would be about 20.9.

Survey Simulation

The approach taken was to generate a set of 1000 synthetic NEO orbital elements, matching the distribution statistics of the actual NEO swarm as best we can determine that from the present sample of known NEOs. We imposed one "unnatural" restriction: we included in the sample only orbits which pass within 0.05 astronomical unit of the Earth's orbit. As a general rule, asteroids whose orbits do not pass within 0.05 AU of the Earth's orbit pose no threat of collision on a time scale of a century, as the planetary perturbations necessary to reduce the miss distance to zero require longer than that to make such a change. Thus we have limited our sample to a subset of the actual distribution: the ones that actually pose a potential threat. Our results don't appear to be very much affected by this restriction, but it is reassuring to know that we have prejudiced the distribution in favor of the more hazardous objects.

Having created a set of synthetic orbit elements, we then generated a set of positions for each object, one for each lunation (new moon) for ten years, or 125 positions for each object. For each computed position, we also calculate the rate of motion on the sky and a relative magnitude which takes into account the distances from the Earth and Sun, and the solar phase angle (analogous to the "phase of the moon", which in a like way very much affects the brightness of the object).

To conduct a survey simulation, we "filter" the file of 125,000 positions to tabulate which objects are "discovered" and which are not. The various "filter" elements include limitations on the sky area viewed, either those imposed by the maximum area the putative system can cover or those naturally existing due to horizon limits, Sun or Moon in the sky, too close to the galactic plane, where detections are impossible due to background star confusion, and most important, object size/system limiting magnitude. On this latter point, we note that the system limiting magnitude and the absolute magnitude of objects are 100% correlated parameters. That is, a system capable of detecting objects 4 times fainter than another system will achieve the same level of completeness of NEOs at 1/2 the diameter as the other system. Thus in estimating completeness vs. size of NEOs, we needn't do independent evaluations for different limiting magnitudes. The same "completeness curve" applies for completeness vs. size at a given threshold magnitude as applies for completeness vs. threshold magnitude for a given size of NEO.

Observational Strategy

Even the basic *detection* of an asteroid requires multiple observations. The method used by the only operational system, Spacewatch, is to scan the same area of sky three times, separated by ~1 hour each. The images are compared to reveal any moving object, with the third scan as a confirmation against erroneous or confused images in either of the other two scans. It is anticipated that the systems described above would operate in a similar mode. Some economy could be achieved by storing a catalog of the sky from past (previous months or years) scans of the same area, so that only two new scans, to be compared against the archival catalog, would suffice. Thus the first step, detection and confirmation of a moving NEO, requires taking two or three scans of a given sky area, separated by an interval of time of the order of an hour or two. This results in a measurement of the instantaneous position in the sky and a rate of motion, which is sufficient for finding the object sometime later, for example the next night.

In order to obtain even a preliminary orbit for the object, further observations are needed. Present practice is to identify NEO candidates on the basis of anomalous rate of motion compared to main-belt asteroids, as determined on the first night of observation. For these objects, additional observations are needed, on at least two more nights, and preferably spaced over an interval of about a week. A one week "arc" is usually sufficient to make a preliminary estimate of the "minimum orbit intersection distance" (MOID) from the Earth and determine whether the object presents any potential hazard to the Earth on a timescale less than a century. A longer arc is necessary to consider the object reliably "cataloged", but with only a week arc the number needing further follow-up, on the strict basis of hazard alone, can be reduced to a small enough number to be accomplished with modest resources.

With highly automated systems, recording detections at much higher rates than present systems, it may become more efficient to just cover the sky often enough that the week-arc follow up occurs automatically, for everything. This has the advantage that all objects are followed up to the level of a preliminary orbit determination. Thus the few NEOs which chance to be mimicking main-belt motion at the time of detection are discriminated and become "discovered." To operate in this mode requires covering the search area about 4 times each month, rather than once plus targeted follow up.

In summary, "detection" consists of a sequence of two or three observations on a single night, which are usually sufficient to distinguish a main-belt object from an NEO and to find it again the next night. To "discover" the object, in terms of a preliminary orbit, requires two or three more observations over about a week, and represents about a doubling of resources over detection alone.

Survey Completeness vs. Area of Sky Coverage

For our first simulations, we specified the area of sky covered per month as the radius of a circle on the celestial sphere centered on the opposition point, which is generally the most productive area to search. In this experiment we made no restrictions for horizon or closeness to the galactic plane. For the detection threshold, which is a combination of telescope limiting magnitude and size of object, we chose limiting magnitudes appropriate for a single GEODSS telescope equipped with the Lincoln Laboratory GUPS CCD chip, with exposure times appropriate to allow coverage of the area of sky assumed in each case. For size of object, we took the brightness corresponding to a 1 km diameter object of albedo 0.15 (typical S class albedo), or equivalently, a 2 km object of albedo 0.04 (somewhat darker than average C, D, etc. objects). In Figure 1 we plot the rate of detections of NEOs for three assumed sky areas corresponding to circles of radius 34°, 65°, and 137° out from the opposition point. For the focal plane instrumentation assumed, these sky areas correspond to exposure times per single image of 100 sec, 30 sec, and 10 sec, respectively. With these exposure times, the specified sky areas can be covered three times (the redundancy required for detection and confirmation) in ~100 hours of observing time, which is the typical amount of time available from a given site in a month, allowing for weather and other types of interruptions. The 34° and 65° sky areas are probably achievable from a ground-based site. 137° corresponds to covering the whole celestial sphere down to a solar elongation of only 43°, clearly not possible from anywhere on the ground without serious losses from atmospheric extinction. The point of this figure, which is a very robust result and applies for any system we have evaluated, is that it is better to cover more sky and sacrifice limiting magnitude as necessary, until all available sky is being surveyed.

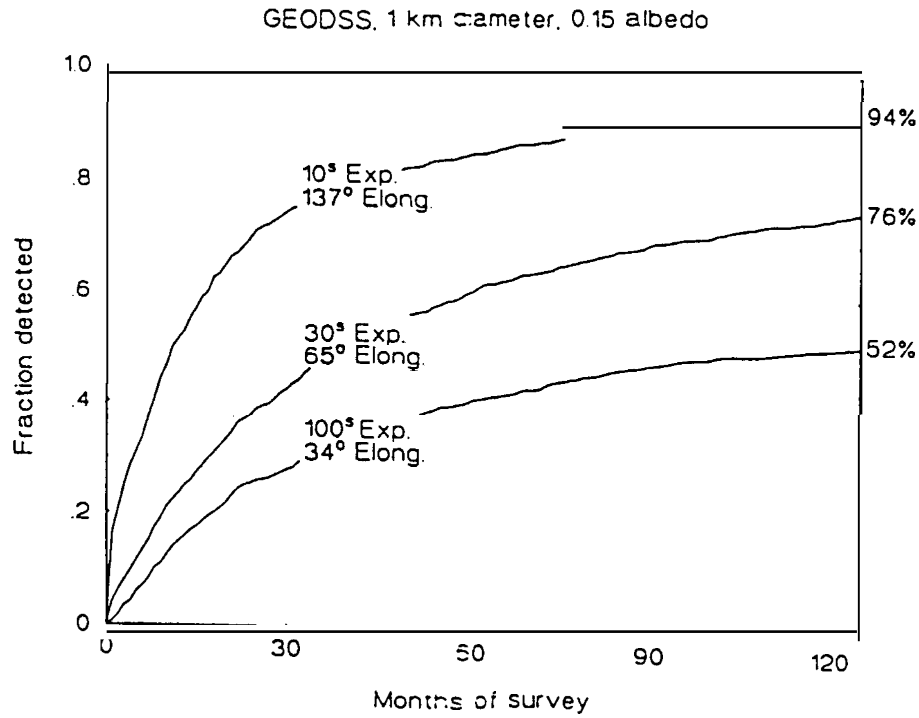

Figure 1. Rate of discovery *vs.* time for one GEODSS telescope. Each curve represents a different choice of exposure time, and consequently limiting magnitude, and results in a different area of sky per month that can be covered. The curves represent the discovery rate for ~1 km diameter objects of moderate albedo (0.15), or ~2 km diameter objects of low albedo (0.04).

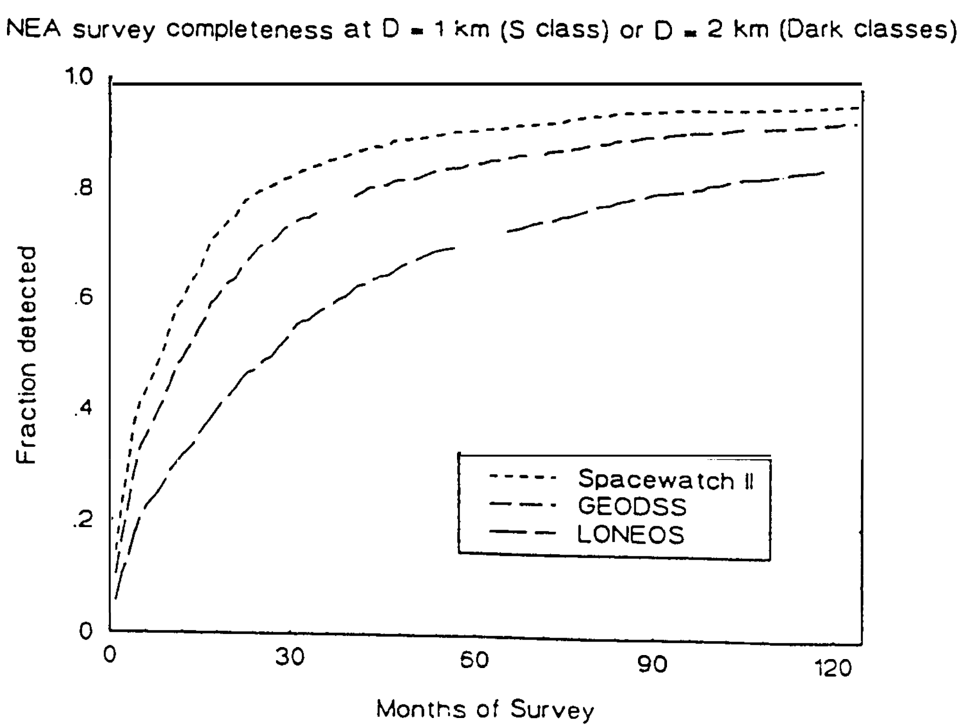

Figure 2. Rate of discovery *vs.* time for each of the three systems evaluated, assuming that the rate of sky coverage is chosen such that all available sky area is covered each month. The curves represent the discovery rate for ~1 km diameter objects of moderate albedo (0.1 5), or ~2 km diameter objects of low albedo (0.04).

All-sky Surveys

Having established that the optimum strategy is always to cover all available sky each month, we concentrated on this mode of operation in the remaining analyses. We first evaluated how much sky is accessible and how many hours are available to cover it for each month of the year. The restrictions applied are:

1. The Sun must be more than 10° below the horizon.
2. The moon must be below the horizon.
3. The target area must be more than 25° above the horizon at some time during the night.
4. The target area must be more than 20° away from the galactic plane.

Subject to these conditions, we determined that, almost independent of station latitude, the maximum rate of sky coverage required is ~135 square degrees per hour in order to cover all of the sky once per month. Allowing for duty cycle losses, cloudy weather, and other down time, the rate of sky coverage should be ~200 square degrees per hour to cover the whole sky once per month. It is important to note here that any system intended to contribute seriously to the survey itself, rather than serve as a "test bed", should be designed to cover sky area at the above rate. Indeed, unless a separate system of astrometric follow-up is contemplated, the survey system needs to be capable of 2 or 3 times that rate to assure enough observations to derive preliminary orbits for the discovered objects.

In Figure 2 we plot the fraction completeness vs. time for each of the three systems described above. For both LONEOS and Spacewatch - II, we have assumed the "full-up" configurations described above which would be capable of all-sky coverage each month. These curves represent the fraction of objects detected, and do not allow for the necessary work of follow-up observations to determine orbits for detected objects, which will be discussed later in this chapter.

Completeness as a Function of Size of NEO or Limiting Magnitude of System

As noted above, the question of whether or not an NEO is detected, given that it passes within the surveyed area, is a function of only one parameter: brightness compared to the detection threshold of the survey system. Thus size and albedo of NEO and threshold limiting magnitude of the detection system all collectively constitute only a single variable. So we can derive a single "completeness curve" which can be used to describe completeness as a function of limiting magnitude of the survey system, for a given size and albedo of object, or equivalently, completeness as a function of size of body, for a system of specified threshold detection magnitude.

Figure 3 is a plot of that function derived from the simulated 10-year survey of 1000 objects. The vertical scale is simply the fraction of the 1000 objects "detected". The horizontal scales are either relative size of object, or threshold detection limit of the system. We have plotted the curve twice (dashed lines), offset by a factor of 2 in diameter (1.5 magnitudes brightness), which correspond the difference of approximately a factor of 4 in albedo between the brighter, "S-Class" asteroids and darker, "C-class" and related types. Among measured NEOs, the ratio of high to low albedo objects is approximately 10:1. However this is strongly affected by the fact that dark objects of a given size are much more difficult to detect. Thus we suspect the bias-corrected ratio is closer to half each, at a given size. The solid line curve in Figure 3 is an equally weighted average of the two dashed curves, and represents the completeness curve for an NEO population consisting of equal numbers of high and low albedo objects. We will use this curve for further analyses.

In Fig. 4, we have plotted the completeness curve to represent completeness vs. diameter of NEO, for various values of system limiting magnitude. In Fig. 5, we present the completeness curve, this time scaled vs. limiting magnitude of the system, for various diameters of NEOs. In addition to the three systems discussed above, we have included curves for the current Palomar 46-cm Schmidt photographic system and for the suggested "Spaceguard Survey" system (see Appendix 1) of 2-3m telescopes capable of surveying to a threshold magnitude of 22. From these plots, it appears that a system reaching limiting magnitude 20 can achieve about 80% completeness of NEOs down to a size of 1 km diameter in a 10-year survey.

Strategies for Preliminary Orbit Determination

One can contemplate two strategies to determine orbits rather than merely detect objects. One way is to do targeted follow-up observations, either by assigning the observations to a second telescope or by taking time from the discovery survey to make these observations. A second mode is to cover the whole sky so often that repeated detections of the same object are sufficient to yield orbit solutions from the regular survey observations. Figure 6 is a comparison of these two follow-up strategies, which we now describe.

Presently, surveys are done in the first mode, of targeted follow-up. To make the problem tractable, it is necessary to discriminate NEOs from the much more abundant main-belt (MB) objects based on motion in the sky, before an orbit is known. Thus there is a "blind spot" of slow sky motion where an NEO can mimic a MB object and thus not be discriminated. As we go to surveys reaching to fainter magnitude, discoveries will be made at greater distances, thus at slower average motion, and the "blind spot" becomes a more significant loss factor. To evaluate this mode of follow-up, we have computed a second completeness curve, this time filtering out objects which, even though they may be in an observable part of the sky at a given time, are exhibiting main-belt-like motion, and thus would not be "noticed". From past experience (e.g. Spacewatch, Palomar photographic), the "overhead" of follow-up of past discoveries appears to be a task of the same magnitude as the survey itself. Thus a survey telescope may be occupied about half time taking follow-up observations and half surveying new sky. Or if two telescopes are available, one could scan while the other does follow-up. In either case, the "cost" is a factor of two in exposure time that could be devoted to survey -only, which translates to ~0.4 magnitude in threshold detection. So we shift the "targeted follow-up" curve 0.4 magnitudes to the right.

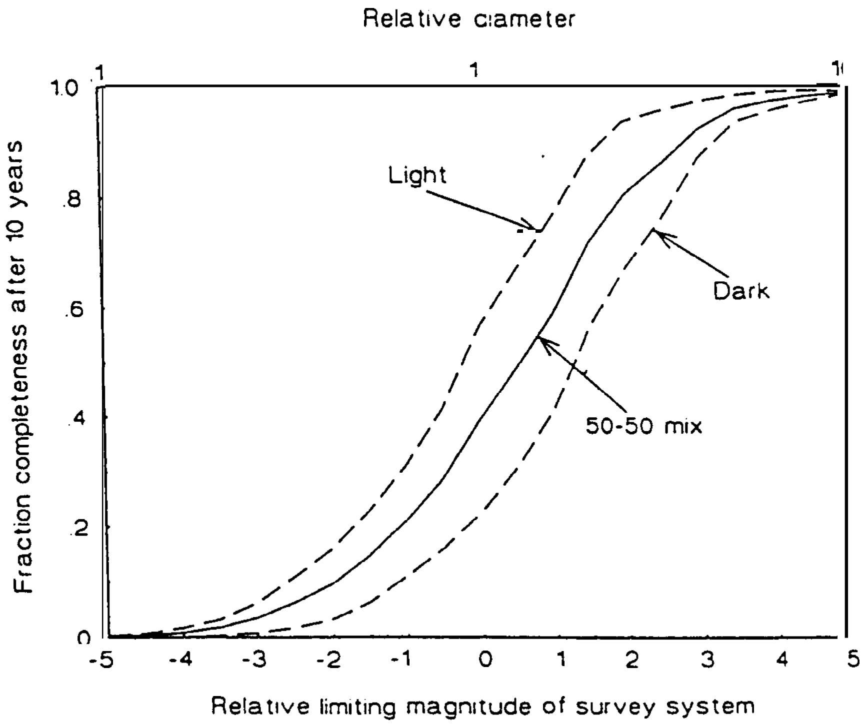

Figure 3. Completeness as a function of limiting magnitude of survey systems. Light refers to a population with albedo equal to average S-type (light) asteroids and dark refers to asteroids with albedo equal to average C-type (dark) asteroids.

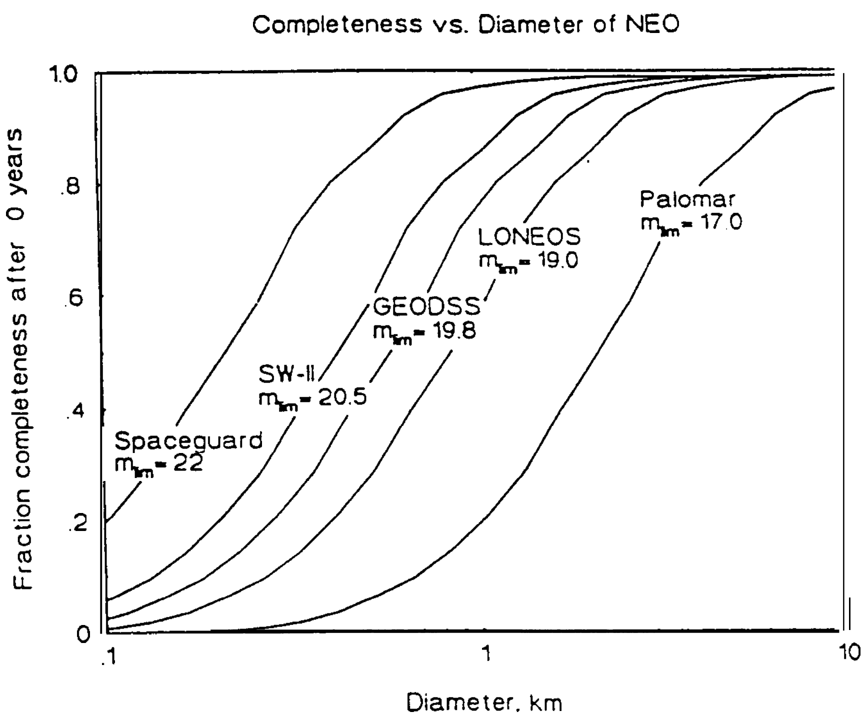

Figure 4. Completeness as a function of asteroid diameter for five survey systems described in text

The second possible follow-up mode consists of simply scanning the sky more often, so that enough positions are obtained of each object to derive a preliminary orbit of every object detected. Thus even those exhibiting normal MB motion are discriminated. For the same threshold magnitude, this technique would obviously discover more objects. However, it is likely that operation in this mode would require covering the sky many times per month, perhaps 4, to assure that at least three observations, each separated by several days, would be obtained of a given object. Thus the "cost" is a factor of 4 in exposure time, or ~0.8 magnitude. So we shift the other curve in Figure 6, 0.8 magnitude to the right.

The result is that the two curves cross one another, so the strategy of targeted follow-up is superior except for the very largest objects. On the other hand, it is the very largest objects which are most important. A pedantic reliance on anomalous motion leads to a worrisome result that no survey, no matter how sensitive, can achieve >90% completeness in 10 years. But the largest objects are also brighter, and very much less numerous, than smaller objects. Furthermore, any large object mimicking main-belt motion will be there the next month for repeat coverage. Thus a hybrid strategy should be possible which could closely approximate the higher level of the two curves over the entire range. In any case, the problem of following up to the point of preliminary orbit determination is roughly a "factor-of-two" complication over bare detection only.

Returning briefly to Figs. 4 and 5, We have associated " LONEOS" with a limiting magnitude of 19, whereas we estimate it is capable of reaching 19.4 in an all-sky survey mode with 68 second exposures. Thus the limiting magnitude of 19.0 is about correct if that telescope is tasked with doing its own targeted follow-up, consuming half its time. The limiting magnitude of 20 associated with GEODSS is about the expected performance of one GEODSS telescope, full time surveying. Thus in truth, this curve represents the capability of two GEODSS telescopes, one surveying and a second one doing follow-up, or some similar combination. The magnitude limit of 21 associated with SW-II is the limit expected for single-coverage of all sky, so again, to achieve this level of performance would require a second 2m telescope, or perhaps a highly automated version of SW-I could keep up with the task. Finally, the limit of 22 associated with "Spaceguard" is in a sense "by definition. " In the Spaceguard Report (see Appendix I) a requirement was defined to achieve nearly all-sky surveying to limiting magnitude 22. That requirement was then estimated to correspond to a system of about five 2-to-3 m telescopes equipped with CCD arrays. We concur with that scale of instrumentation required to achieve all-sky coverage to magnitude 22.

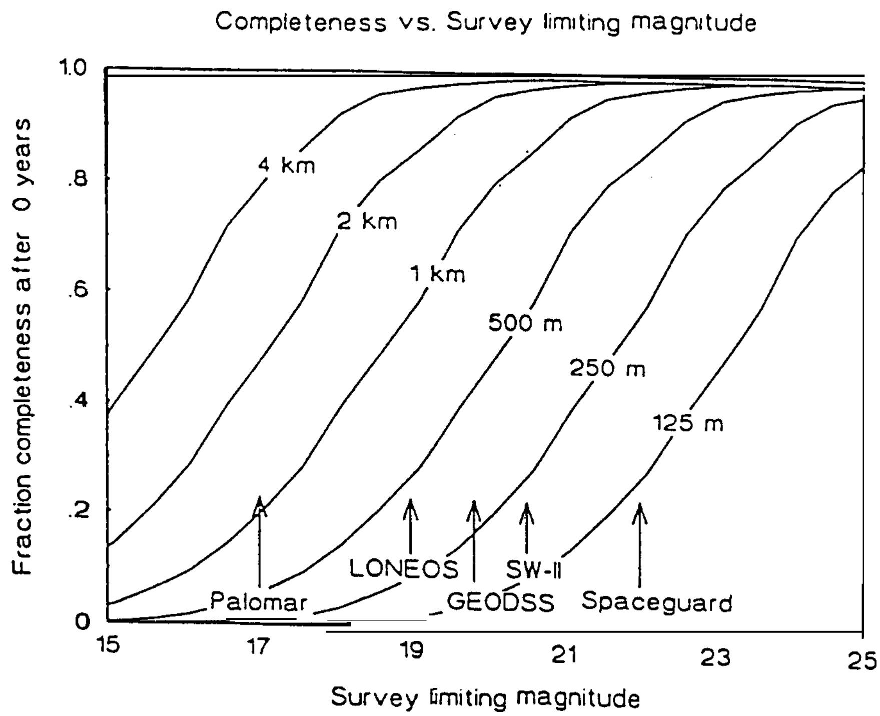

Figure 5. Completeness as a function of limiting magnitude of survey telescopes.

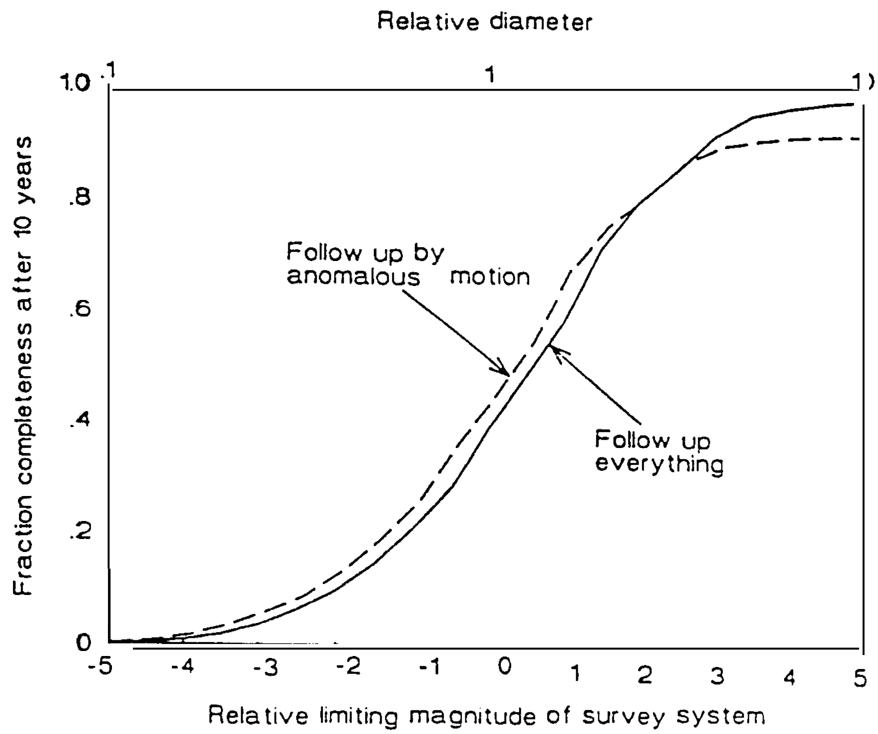

Figure 6. Completeness as a function of limiting magnitude of survey systems with two different strategies for preliminary orbit determination (see text).

Conclusion

If one asks the question, what is the likely largest size of any remaining undetected object (that is, where completeness equals one over the number of objects of that size expected), the answer is about 3 km for the evaluated systems, after 10 years. Pushing this limit down to ~1 km would require a Herculean effort. Thus we must accept some level of incompleteness. The systems evaluated can yield completeness in the range 80-90% or better, especially if all are used in concert. This level of completeness should reduce the threat from collision by an undetected NEA to less than that posed by impacts from long-period comets, so in that context, we can declare these systems capable of achieving the Spaceguard goal of reducing the hazard of asteroid collision by an unknown object to below that from comets.

The most important lesson which emerges from this analysis is that the best survey strategy is to cover the entire accessible sky every month, sacrificing whatever magnitude limit is necessary to accomplish this. A very positive result is that if that strategy is followed, adopting reasonable and even conservative limit on sky observability, it is possible to obtain reasonable completeness in ten years, including objects which never quite reach out to the orbit of the Earth and hence never come to opposition. Thus the ability to observe closer to the sun or to remove horizon limitations is not a sufficient justification in itself to move to a space-based survey system.

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